Evidence for an Intense Neutrino Flux during r-Process Nucleosynthesis?

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ABSTRACT

We investigate the possibility that neutrino capture on heavy nuclei competes with beta decay in the environment where the r-Process elements are synthesized. We find that such neutrino capture is not excluded by existing abundance determinations. We show that inclusion of significant neutrino capture on the (neutron number) N=82 waiting point nuclei can allow the inferred abundances of these species to provide a good fit to steady weak (beta decay plus neutrino capture) flow equilibrium. In fact, for particular choices of neutrino flux conditions, this fit is improved over the case where nuclei change their charge by beta decay alone. However, this improved fit can be realized only if neutrino capture plays a negligible role in nuclear decay back toward stability. We discuss the implications of these considerations for current proposed sites and models for r-Process nucleosynthesis.

Subject Headings: elementary particles - nuclear reactions, nucleosynthesis, abundances - stars: supernovae

1. Introduction

Many elements heavier than the iron peak, and about half of nuclei heavier than mass $A > 100$, are believed to be synthesized in the r-Process (or rapid neutron capture process; Burbridge et al. 1957; Cameron et al. 1957; For a recent review see Meyer 1994). The r-Process is thought to take place in conditions of (n,γ), (γ,n) equilibrium. (cf. Kratz et al. 1988, Kratz et al. 1993). Measurements of abundances of r-process nuclei show that peaks exist around the closed neutron shells, occurring at neutron numbers N=50, N=82, and N=126. In particular, the relative abundances of the r-Process progenitor elements can be determined to accuracies of order $\sim 20\%$ in the vicinity of the N=82 (nuclear mass number A $\approx$ 130) abundance peak (Kratz et al. 1988). This determination involves first subtracting the predicted s-process contribution from the measured solar abundance for each stable nuclide. The r-Process progenitor abundances then are inferred from beta decay lifetimes and the estimated probabilities for beta-delayed neutron emission along the decay path back to stability.

In (n,γ), (γ,n) equilibrium, the abundance distribution along an isotopic chain often can be strongly peaked at one or a few nuclear species around the closed neutron shells. We define $Y(Z)$ to be the abundance of the nuclide at the abundance peak for an isotopic chain Z. In the limit where $Y(Z)$ is approximately equal to the total abundance along isotopic chain Z, the dominant source of leakage from isotopic chain Z to chain $Z+1$ will occur through the beta decay of this nucleus at the abundance peak. We define the beta decay rate of this nuclide to be $\lambda_\beta(Z)$. Usually, such a "waiting point" nucleus will have a closed neutron shell. Conditions of local steady nuclear flow (time independent abundances) would correspond to a constant value of the product $Y(Z)\lambda_\beta(Z)$ over some range of nuclear charges. This is sometimes termed steady beta flow equilibrium (cf. Cameron, Cowan & Truran 1983). We can define the beta flow ratio $R_\beta(Z,Z')$ for isotopic chains Z and Z' to be,

$$R_\beta(Z,Z') \equiv \frac{Y(Z)\lambda_\beta(Z)}{Y(Z')\lambda_\beta(Z')}. \tag{1}$$

If Z and Z' are within the range of nuclear charges where a local steady beta flow obtains, then we would expect $R_\beta(Z,Z') = 1$. Obviously, these considerations for defining steady beta flow would have to be modified if there are two or more isotopes which are significantly populated in a given isotopic chain.

Conditions of steady beta flow and $(n,\gamma),(\gamma,n)$ equilibrium could occur in many of the diverse environments which have been suggested as possible sites of origin for r-Process nucleosynthesis (for reviews see Mathews & Cowan 1990; Cowan, Thielemann & Truran 1991; and Meyer 1994; and references therein). However, two proposed r-Process sites could occur in intense neutrino fluxes: decompression of cold neutron matter from neutron star mergers (cf. Meyer 1989; Lattimer et al. 1977); and neutrino heated supernova ejecta (Woosley & Hoffman 1992; Meyer et al. 1992; Woosley et al. 1994; Janka, Takahashi & Witti 1994). The processes of neutrino and antineutrino capture on heavy nuclei:

$$\nu_e + \mathrm{A(Z,N)} \rightarrow \mathrm{A(Z+1,N-1)} + e^-; \tag{2a}$$

$$\bar{\nu}_e + \mathrm{A(Z,N)} \rightarrow \mathrm{A(Z-1,N+1)} + e^{+}, \tag{2b}$$

produce the same nuclear charge changing effect as beta decay (positron capture) and positron decay (electron capture), respectively, though the nuclear dynamics and energetics of these processes can be very different (cf. Fuller & Meyer, 1995 hereafter FM95; McLaughlin & Fuller, 1995 hereafter MF). For the neutron-rich nuclei which are of interest in the r-Process and for the neutrino and antineutrino energy spectra expected from hot nuclear matter, only neutrino capture (equation 2a) could play an important role (FM95; MF). If the rates of neutrino capture on the waiting point nuclei in the r-Process compete favorably with the corresponding beta decay rates, then we could expect significant alterations of our picture of steady flow equilibrium (FM95; Nadyozhin & Panov 1993).

Neutrino capture on heavy nuclei could be important if the neutrino flux is large and/or if the neutrinos have high energies. The neutrino capture rate, λ_ν, depends both on nuclear physics and on the properties of the neutrino flux. For example, assuming that the neutrino flux originates from a spherical hot proto-neutron star, the following rough dependence holds (FM95; MF):

$$\lambda_\nu \propto L_\nu T_\nu r_7^{-2} |M|^2 P. \tag{3}$$

Here, L_ν is the energy luminosity of the neutrinos, T_ν is the temperature of the electron neutrino distribution function (assuming the neutrino chemical potential is $\mu_\nu \approx 0$), and r_7 is the distance from the center of the neutron star in units of 10^7cm. The characteristic nuclear matrix element is $|M|^2$, and P is a characteristic phase space factor. Given a sufficiently energetic neutrino distribution function, we expect neutrino capture to be dominated by transitions to the Fermi and Gamow-Teller Resonance states (cf. Figure 1 of FM95). These weak strength distributions peak at excitation energies which are at least the coulomb energy difference between the parent and daughter nuclei plus the parent-daughter mass difference. We caution that the dependence of λ_ν on the various ingredient quantities in equation (3) is highly dependent on the particular geometry of our example (neutrino-heated supernova ejecta from a hot proto-neutron star). Alternatively, if we were to consider outflow from merging neutron stars, then we could obtain similar values of λ_ν and r-Process effects of neutrino capture, though the dependence on the geometry and neutrino distribution function parameters could be significantly different than in the supernova case.

2. Steady Beta Flow vs. Steady Weak Flow

We have calculated the ratios R_β for elements in the N = 82 peak. The beta decay rates we used (Kratz et al. 1988; Tuli 1990) are shown in Table 1. In general, the heavier elements tend to have slower beta decay rates since these also have larger Z, and thus are closer to stability. The abundances used (Kratz et al. 1988) are shown in Table 1. The resulting values of R_β are shown in Table 2. The R_β ratios have been calculated with the heavier (more stable) element always in the numerator, and the lighter element always in the denominator. These values fall systematically below unity. This systematic

trend has not been pointed out before. However, the R_β values in Table 2 usually are taken as evidence for steady beta flow in the r-Process, since the characteristic abundance errors are believed to be of order $15-20\%$ and the R_β values differ from unity by roughly that amount. Unless there are systematic, non-Gaussian normal errors in the abundance determinations, it is difficult to understand why these R_β ratios are systematically low. Although most of the elements in the abundance peak are concentrated in the N=82 isotopes, a small component in another isotope will cause a deviation of the ratios R_β from unity. Below we will argue that ν-capture could explain this result, however, Thielemann (1996) has suggested that a superposition of several distinct neutron exposure conditions could account for the systematic trend evident in Table 2. There remains the question of whether the particular temperature, density, and Y_e (electron fraction) tracks proposed in, for example, the Woosley et al. (1994) or the Qian & Woosley (1996) ejection trajectories provide the requisite superposition of conditions to explain the trend. Note that we have employed ground state beta decay rates in Tables 1 and 2. If the r-Process is occurring in high temperature environments, then there may be an acceleration of the beta decay rates resulting from thermal population of excited nuclear parent states.

However, we note that a modicum of neutrino exposure can lead to an interesting interpretation of the trends in Table 2. To take account of the possibility that neutrino capture, as well as beta decay, contribute to the rate of weak leakage from one isotopic chain to the next, we define,

$$R_{\beta+\nu}(Z,Z') \equiv \frac{Y(Z)(\lambda_\beta(Z)+\lambda_\nu(Z))}{Y(Z')(\lambda_\beta(Z')+\lambda_\nu(Z'))}, \tag{4}$$

where $\lambda_\nu(Z)$ and $\lambda_\nu(Z')$ are the neutrino capture rates on the waiting point nuclei of charge Z and Z', respectively, while the other notation is as in equation 1. Clearly $R_{\beta+\nu}=1$ if steady flow equilibrium prevails over the region of the abundance peak which includes Z and Z'. We will term this condition steady *weak* flow equilibrium.

The evaluation of $R_{\beta+\nu}(Z,Z')$ is more difficult than the calculation of $R_\beta(Z,Z')$. The neutrino capture rate will vary according to the properties of the neutrino flux and distance from the neutron star or other neutrino source. Also, the rate will vary between nuclei due to differences in characteristic matrix elements and the excitation energy of the Fermi and Gamow-Teller resonances. Our calculations of the neutrino capture rates for the $N=82$ waiting point nuclei have been tabulated in Table 1. These computations of the neutrino capture cross sections conform to the method of FM95 and MF, except we here include a full numerical calculation of the energy dependent phase space factors and Coulomb wave correction factors (McLaughlin & Fuller 1996). For these specific rates in Table 1, a neutrino luminosity of $L_\nu = 10^{51}\mathrm{ergs\,s^{-1}}$ and a ν_e neutrino sphere temperature of $T_\nu = 3.1\,\mathrm{MeV}$ is assumed. These latter conditions are consistent with those obtained at late time ($t_{pb}\approx 7s$), where most of the N=82 nuclei are made (Woosley et al. 1994). Using these conditions, and a distance of $r_7 = 0.8$, we find that the ratio $R_{\beta+\nu}\approx 1$ in all cases. The $R_{\beta+\nu}$ ratios for $r_7=0.8$ are shown in Table 3. These results demonstrate that significant neutrino capture could be tolerated in some models of r-Process nucleosynthesis. Note that the neutrino flux parameters and the distance to the neutron star may be varied

as long as the value $L_\nu T_\nu r_7^{-2}$ remains the same, at least in the context of the model of r-Process nucleosynthesis from supernova outflow. If the radius is increased by a factor of 2, the luminosity or temperature must decrease by a factor of 4. Other possible alterations to the capture rates are discussed below.

Additional variance in neutrino capture rates between nuclei could be found through differences in the placement and width of the Gamow-Teller strength. The excitation energy distribution of this strength is uncertain (FM95, MF). The Gamow-Teller strength distribution width in the N = 82 nuclei may be varied to effect an increase in the neutrino capture rate in these species by a factor of about ~ 2. The neutrino capture rate calculations presented in Table 1 are based on the assumption that the Gamow Teller resonance was located at the same excitation energy as the Fermi strength. If the Gamow-Teller strength centroid is pushed upward by about 4 MeV in excitation energy, then the neutrino capture rate could decrease by as much as a factor of ~ 2. Such effects could cause significant rate variations between nuclei. In the case of the nuclei examined in Tables 2 and 3, all $R_{\beta+\nu}$ ratios are close to unity when calculated with the given neutrino flux parameters. If the capture rate for one nucleus were to change (e.g. from a change in the width or centroid of the Gamow-Teller strength), then all the ratios $R_{\beta+\nu}$ would be driven further from unity when an attempt is made to find a new concordant r_7 value.

3. Discussion

First, we must note that in the particular environment of the post-core-bounce Type II supernova, an r-Process at $r_7 \sim 1$ is in conflict with the models based on the high entropy bubble in the Wilson and Mayle supernova calculations. At the high entropy per baryon $s/k \approx 400$ obtained in these models, the r-Process goes on at, or above, about 600 km - 1000 km (Woosley et al. 1994; Meyer et al. 1992). However, if the entropy at this time were lower, $s/k \approx 100$, then heavy element nucleosynthesis ($(n, \gamma), (\gamma, n)$ equilibrium) could conceivably occur much closer to the neutron star, with $r_7 \sim 1$ not out of the question (see for example the calculations of Qian & Woosley 1996 where it is argued that the entropy must be less than $s/k \approx 200$). Production of r-process elements in this scenario requires further investigation into the velocity field and electron fraction of the outflowing material. Other numerical supernova models (e. g. the models on which the Takahashi, Witti & Janka 1994 calculation are based) seem to get such low entropies. Burrows, Hayes & Fryxell (1995) also seem to obtain low entropy, though it might be argued that these calculations do not probe the late epochs where the r-Process might occur. In any case, it is not obvious that any of the existing r-Process models based on neutrino-heated supernova ejecta could give $(n, \gamma), (\gamma, n)$ equilibrium freeze-out for the N = 82 nuclei at $r_7 \sim 1$. This implies that either: (1) the trend in Table 2 does not arise from neutrino capture; (2) models of the r-Process from supernova ejecta need to be altered; or (3) the r-Process originates in some other site.

In the Woosley et al. (1994) calculations, mass elements (trajectories in their terminology) which leave the neutron star at progressively later times tend to be responsible for the production of progressively heavier r-Process nuclear mass ranges. It is clear that neutrino

capture can dominate over beta decay throughout the stage of the r-Process leading up to the establishment of $(n,\gamma),(\gamma,n)$ equilibrium. Indeed, this can accelerate the r-Process, (Nadyozhin & Panov 1993), and perhaps explain how the "scale height" of models could be reduced. However, neutrino capture must be comparable or subdominant to the beta decay rates of the waiting point species when freezeout from $(n,\gamma),(\gamma,n)$-equilibrium occurs.

It would be desirable to examine steady weak flow in the N=50 peak nuclei in a manner similar to our treatment of the N=82 nuclei. Unfortunately, due to difficulties in extracting the r-Process component of the measured abundances for these species, the inferred progenitor abundances (e.g. ^{80}Zn), are more uncertain than those inferred for the N=82 abundance peak (Kratz et al. 1988). This makes analysis of the weak flow in this region difficult. Fuller & Meyer (1995, 1996) considered the ratio of ^{80}Zn to ^{79}Cu. They found that if steady beta flow is assumed ($R_\beta = 1$ to within 20%), then a significant rate of neutrino capture on heavy nuclei is not tolerable. In fact, they employed their calculations to place a limit of $r_7 > 4$ on the location of $(n,\gamma),(\gamma,n)$- equilibrium freezeout for the N = 50 nuclei. This limiting value of radius depends quite sensitively on the value of R_β. Therefore, it would be desirable to know a more precise value of the progenitor abundances in order to make a determination of the prospects for significant neutrino capture contributions to steady weak flow in this case. Furthermore, in models of neutrino-heated supernova ejecta, the N=50 nuclei are primarily made much earlier than are the N = 82 species. The neutrino-heating history, outflow velocity, and other parameters could be quite different at this earlier epoch. Therefore, it is conceivable that the Fuller & Meyer (1995, 1996) limit on the location of the N = 50 freezeout could be consistent with significant neutrino capture in the N = 82 species, at least within the context of the r-Process originating in supernova ejecta.

If neutrino capture can affect steady weak flow equilibrium, then would it not also play a role during the decay back toward stability? Neutrino capture-induced neutron emission would be greatly enhanced over beta-delayed neutron emission, since neutrino capture could access the considerable Gamow-Teller and Fermi strength which resides at daughter nucleus excitation energies above the neutron separation energy for the r-Process progenitor species (FM95). Indeed, populating the region of excitation energy near the isobaric analog state or Gamow-Teller peak could result in multiple neutron emission. Clearly, if such processes operate during decay back toward stability in the r-Process, then the inference of the progenitor abundances from the measured stable species abundances could be quite significantly different from the results of Kratz et al. (1988, 1993). In this event, our discussion of neutrino capture contributions to weak steady flow based on the Kratz et al. (1988, 1993) progenitor abundances would be specious, and the remarkable results of Table 3 merely an accident. For this scenario, perhaps the Thielemann (1996) suggestion for explaining the trends in Table 2 will prove to be correct, in which case neutrino capture will serve to drive the $R_{\beta+\nu}$ ratios further from unity. Such an effect could allow for very useful and stringent constraints on the location of the $(n,\gamma),(\gamma,n)$-equilibrium freezeout in various models for the r-Process.

However, the rapid outflow of material inherent in some models of the r-Process suggests an alternative resolution to the inconsistency of significant neutrino capture in both weak steady flow and during decay back toward stability. As a working example, let us

consider models of the r-Process inspired by the rapidly outflowing, neutrino-driven wind in the post-core-bounce supernova environment. Here, we would expect neutrino capture capture and decay back toward stability to be occurring in material which is moving away from the source of the neutrino flux. If indeed neutrino capture is as significant in steady weak flow as Table 3 suggests, then we know that the neutrino flux must be high enough to give the neutrino capture rates in Table 1 for the N=82 species when this material freezes out of $(n,\gamma),(\gamma,n)$ equilibrium. The condition $R_{\beta+\nu} \approx 1$ in Table 3 suggests that the $N = 82$ nuclei experience this freeze-out at $r_7 \approx 0.8$. If neutrino capture is to play a negligible role in decay back toward stability, then conservatively the mean neutrino capture rates should be less than about one tenth of the beta decay rates. So, for example, for ^{127}Rh, $\lambda_\nu \approx 7.4\,\mathrm{s}^{-1}$ at $r_7 = 0.8$, while $\lambda_\beta \approx 10.35\,\mathrm{s}^{-1}$. A characteristic outflow velocity of $v \approx 10^8\mathrm{cm\,s}^{-1}$ will take the material at the $(n,\gamma),(\gamma,n)$ freeze-out point at $r_7 \approx 0.8$ to $r_7 \approx 2$ in one neutrino capture time. At $r_7 \approx 2$, we will have $\lambda_\nu \ll \lambda_\beta$. An outflow velocity $v \geq 10^8\mathrm{cm\,s}^{-1}$ is just what is expected in recent models. Therefore, the rapid outflow of the material could allow significant neutrino capture influence on steady flow equilibrium, yet minimize neutrino-induced processing during decay back.

Neutrino capture conceivably could populate highly excited states in the daughter nucleus which lie above the fission barrier. Such neutrino capture-induced fission will be most likely for heavier nuclei, including the A $\approx$ 195 peak nuclei, and especially the actinides (Fuller, McLaughlin, & Meyer 1996).

Could neutrino capture-induced fissioning of heavy nuclei halt the r-Process flow before the actinides could be synthesized? Again, rapid outflow could allow lower mass nuclei to experience significant neutrino flux exposure, while the heavier species which are synthesized later experience insignificant neutrino processing. Although this is plausible, it remains to be seen whether detailed models of the r-Process in neutrino-heated outflow can avoid problems with neutrino capture-induced fission or neutrino processing on the decay back to stability.

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Table 1: N=82 Nuclei

	^{130}Cd	^{129}Ag	^{128}Pd	^{127}Rh
λ_β	3.47^a	4.88^a	6.03^b	10.35^b
λ_ν	4.01	4.25	4.49	4.75
$(\lambda_\nu/\lambda_\beta)r_7^2$	1.15	0.87	0.75	0.46
Y	2.28^c	2.05^c	1.76^c	1.24^c

^{a} beta decay rates known experimentally from Tuli (1990)

^{b} beta decay rates calculated by Kratz et al. (1988)

^{c} progenitor abundances from Kratz et al. (1988)

Table 2: R_β Values[a]

	^{129}Ag	^{128}Pd	^{127}Rh
^{130}Cd	0.79	0.74	0.62
^{129}Ag		0.92	0.77
^{128}Pd			0.82

[a] note that the ratios always contain the heavier nucleus' abundance and beta decay rate in the numerator and the lighter nucleus' abundance and beta decay rate in the denominator.

Table 3: $R_{\beta+\nu}$ Values[b]

	^{129}Ag	^{128}Pd	^{127}Rh
^{130}Cd	0.93	0.95	1.0
^{129}Ag		1.0	1.1
^{128}Pd			1.0

[b] neutrino flux evaluated at: $T_\nu = 3.1\mathrm{MeV}$, $L_\nu = 10^{51}\mathrm{ergs\,s^{-1}}$, and $r_7 = 0.8$

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